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Highway De-Icers: Standards, Practice, and Research in the Province of Ontario

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Abstract: Sodium chloride has been used in Ontario and most of North America since the late 1940's to assist in removing ice from highways and to improve the effectiveness of winter abrasives. In recent years, a number of undesirable side effects of salt have been recognized and research has been undertaken both to mitigate these effects and to find alternative de-icing chemicals.

Techniques have been developed to mitigate some of the adverse effects of road salt. Protection of concrete structures from salt runoff and reduction of the rate of corrosion of reinforcing steel have been particularly successful, as has improved automotive design to reduce rusting of vehicles. Preliminary investigations have shown the technical feasibility of rehabilitation of contaminated groundwater and physical protection of roadside plants from salt spray. The economic feasibility of the treatments investigated remains in question.

Of the many chemicals which have been investigated as potential alternatives to salt, only calcium chloride and magnesium chloride, calcium magnesium acetate (CMA), sodium formate, and urea have shown sufficient promise of success that they have been tested in the field. Of these, CMA appears to eliminate the major adverse environmental effects of salt. It is significantly more expensive than salt however, and its effectiveness under severe winter weather conditions is not proven.

Comments: De-icer Fact Sheets which summarize the attributes of a number of de-icing chemicals are available from the Research and Development Branch

Key Words: road salt, alternatives to salt, de-icing chemicals, winter maintenance, snow and ice control, CMA

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1/ Introduction

Winter in Ontario brings with it freezing temperatures, high winds, falling snow, rain and sleet. Between the months of October and April, these phenomena frequently coat the province's highways with ice or packed snow, creating hazardous driving conditions.

The Ministry of Transportation of Ontario (MTO) endeavours to maintain safe driving conditions on highways by removing snow and ice through a program of plowing, sanding and salting.

While plowing is the preferred method of removal, it will not remove ice which is bonded firmly to the pavement, so a de-icing chemical is used. When temperatures are too cold for chemicals to be effective, sand is applied to provide traction on icy or snow-packed surfaces.

Common salt, (sodium chloride), has been the de-icing chemical of choice in Ontario and most of North America since the late 1940's, because it is both economical to use and effective at typical winter temperatures. In recent years, a number of side effects of salt have been recognized, including; promotion of vehicle corrosion, deterioration of concrete structures, damage to vegetation, and contamination of drinking water.

Research has been underway for several years to find means of mitigating the adverse effects of sodium chloride, and to find alternative de-icers. MTO has been in the forefront of this effort. The research is of a highly specialized nature and, since much of it has not yet been concluded, it is not widely disseminated to the public. The purpose of this report is to present state-of-the-art information on highway de-icing in Ontario and the search for economical, effective and environmentally benign alternative chemical de-icers.

2/ Principles of Road Icing and De-icing

2.1/ Causes of Ice Formation

Several processes can result in the formation of ice on highways [1]:

(a) An icy crust is formed by melting and sublimation of the surface of freshly fallen snow. This is bonded only loosely to the road surface and can be plowed off.

(b) Further compaction, especially melting and refreezing due to tire action, forms an icy layer which bonds the snow firmly to the pavement.

(c) Moisture in the air freezes on contact with the road surface to form weakly bonded hoar frost. Radiative cooling and hoar frost formation are especially common on bridge decks which cool from both top and bottom surfaces.

(d) Cold rain freezes on contact with a sub-freezing road surface and forms glare ice.

(e) Ponded water freezes on a road surface to form a thick sheet of ice firmly attached to the road.

2.2/ Thermal and Chemical De-icing

Water will change from a random molecular (liquid) state to a more organized crystalline structure when it loses energy, ie. there is a reduction in temperature of the water. Water molecules are then held in a rigid, low-energy lattice pattern called ice.

This process may be reversed and ice melted, by an increase in energy. In nature, energy for this process is supplied by solar radiation, warm air, rain or soil. When sufficient energy is supplied to raise the temperature of pure ice to 0° C, its vapour pressure is increased to equilibrium with liquid and the ice begins to melt. This is shown as point 'A' on Figure 1.

Vapour pressure may also be changed and the phase equilibrium altered by the addition of water soluble substances called solutes. This is the principle of chemical de-icing.

The change in vapour pressure due to the addition of solutes is illustrated by the dashed line in Figure 1. Lowering the vapour pressure depresses the freezing point of the solution, as shown at point 'B' in Figure 1. The effectiveness of this process depends on the relative number of molecules of water and of solute.

The vapour pressure is lowered and thus the freezing point of the solution is depressed as the number of de-icer molecules relative to ice is increased. Likewise, the rate of reaction is increased since the opportunity for random interaction with molecules in the ice is increased. Thus, solutes with a large number of molecules per unit mass of material will be more effective than those with fewer molecules per unit mass. The relationship between solute concentration and freezing point depression is illustrated for several de-icers in Figure 2 [3].

The theoretical minimum temperature at which a de-icer will be effective is governed by its solubility in ice. The lowest temperature at which a de-icer will form a solution with ice is called the eutectic point (Figure 2). The freezing point depression and the eutectic point are thus the theoretical determinants of the effectiveness of a de-icing chemical.

The rate of dissolution for a given concentration of solute is reduced as temperature falls, and is so low near the eutectic point that the chemical is not useful for highway de-icing. Hence, for each chemical there is a temperature higher than the eutectic point which represents the minimum temperature for effective application. For sodium chloride, the minimum temperature is approximately -12° C.

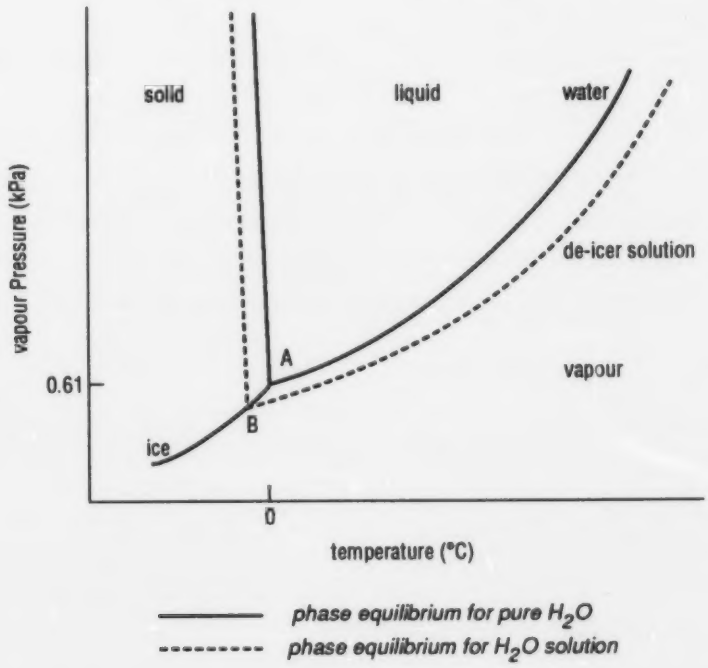

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Figure1/ Phase diagram for H_2O

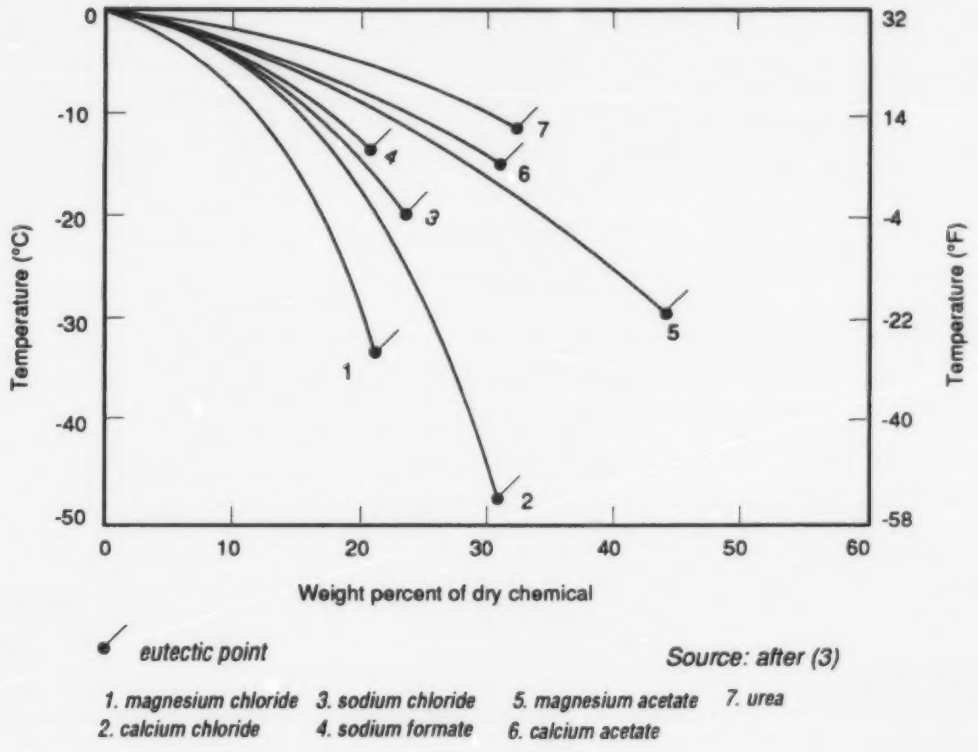


Figure 2/ Freezing point depression and eutectic of various de-icing chemical solutions

2.3/ Mechanical De-icing

Ice does not simply rest on the road surface, but adheres to it; therefore, it cannot be plowed off the road as readily as can snow. Adhesion results from a combination of intermolecular forces between ice and the pavement substrate, and the mechanical interlocking of ice which is frozen into pores on the substrate surface. Tests show that adhesion of ice, measured as shear strength on a substrate, increases as temperature decreases and is in the order of 800 kPa, for ice on concrete at -15°C [4].

Forces which bond ice molecules to one another, as opposed to a substrate, result in cohesion. Cohesive strength is only slightly temperature dependent and has the same order of magnitude as adhesion [5]. This may explain why sheets of ice can be plowed from a pavement surface at temperatures slightly below freezing while at lower temperatures, plowing only chips off small pieces of ice.

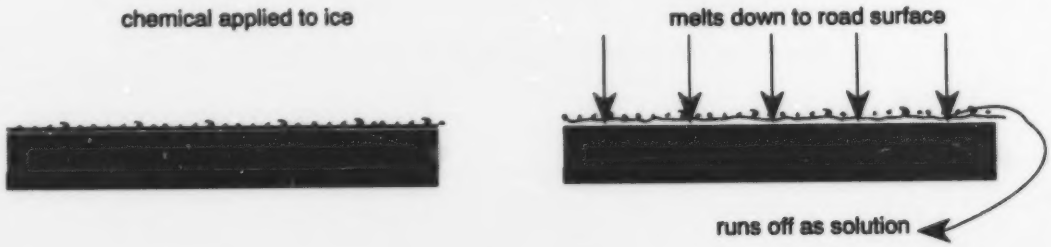
2.4/ Practical Considerations in De-icing

Thermal, chemical and mechanical processes typically are used together to remove ice from highways.

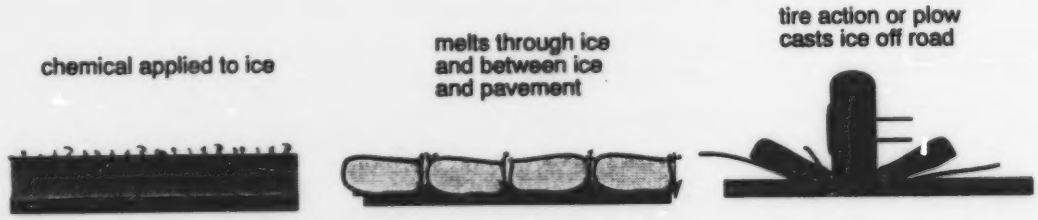
In conditions where snow is bonded weakly to the road, it can be easily cast to the side mechanically, by plowing. As the bond strength increases due to partial melting and refreezing of the snow crystals into ice and to falling temperature, the plow is able to chip off only small pieces. The majority of the ice remains adhered to the road and de-icing chemicals are employed.

In the simple case, the de-icer gradually dissolves with the ice sheet and the de-icer solution drains off the road surface (Figure 3a).

The more typical case involves several processes. The de-icer is applied to the ice surface and melts channels through it to the pavement. The solution then spreads as a thin layer at the interface between the ice and pavement, weakening the adhesion between them. With the adhesive strength thus reduced, the ice can be displaced mechanically by vehicle tires or by plowing (Figure 3b).



3a. Solution of Ice



3b. Solution, Disbondment and Mechanical Displacement of Ice

Figure 3/ Methods of de-icing highways

While the process illustrated in Figure 3a appears more direct, there are several reasons why the objective of de-icer applications in most situations is to weaken adhesion between ice and pavement (a process known as disbonding or debonding) rather than to physically melt the ice sheet. Perhaps the most basic one is economics. Huge quantities of de-icer would be required to melt even a thin ice sheet to bare pavement. For example, tests show that at -7°C, a 3 mm ice sheet on a 2-lane km stretch of pavement can be completely disbonded with 1250 kg of sodium chloride, while complete melting of the same ice sheet would require about 6800 kg (Appendix A) [6, 7].

In practice, much less de-icer is needed for disbondment than is indicated above. An ice sheet can be cleared by plowing long before it is disbonded completely, since the adhesive strength need be reduced only until it is less than the cohesive strength. This requires only partial destruction of the ice-pavement bond. De-icing can be accomplished in most conditions experienced in Ontario with a salt application of about 130 kg per 2-lane km, followed by plowing or other mechanical displacement (see Section 5).

Disbonding is also preferred over surface melting because it provides a more skid resistant ice surface. Disbonding occurs when a de-icer particle bores through the ice to the pavement surface and then a solution of the de-icer spreads at the ice-pavement interface (Figure 3b). This leaves a relatively dry ice surface. Surface melting creates a wet, slippery road surface until the entire ice sheet has melted and the solution has drained off the road (Figure 3a). While it is thus exposed, the solution is susceptible to added dilution from falling snow, and refreezing.

The rate of solution and penetration, and the effective temperature of a de-icer are also affected by particle size. For a given de-icer, smaller particles have a greater surface area per unit mass. Therefore, they dissolve more quickly than the same mass of fewer, larger particles. On the other hand, the particle must be heavy enough that it is not blown off the road and must contain enough de-icer material to maintain the critical concentration of solution until it penetrates to the pavement. If there is a surplus of ice relative to de-icer, the solution surrounding the de-icer particle will refreeze.

Thermal inputs from solar radiation and conduction from the ground also play a role in chemical de-icing. This is particularly true when the ice temperatures are close to the eutectic of the de-icer. The combined effects of an increase in temperature, due to solar or conductive heating and freezing point depression by the de-icer, may melt the ice when neither would be effective on its own. This explains why de-icers may be effective during the daytime but not at night, or why a de-icer which is applied early in the day may be inactive until late morning or early afternoon.

The discussion above describes factors which influence the effectiveness of de-icing methods. Selection of a de-icing method or product involves many other considerations. Chief among these are environmental effects, cost, and, in the case of chemical de-icers, their storage and spreading characteristics.

Chemical de-icers have been in use for five decades. However, recent research has brought to light a variety of adverse properties which detract from the desirability of using these otherwise effective and economical products. Some of the adverse characteristics have associated costs which are easy to measure, while others are more difficult to quantify. Chief among the adverse characteristics are effects on:

- roadside biota and fauna
- drinking water quality
- highway materials
- automotive materials
- safety of personnel

The adverse properties as well as effectiveness should be considered in determining the overall suitability of a de-icer for use on public highways.

2.5/ Innovative Approaches

In addition to the traditional approaches involving alternative chemicals, a number of innovative methods of de-icing are being investigated as part of the United States Strategic Highways Research Program [8, 9]. These projects include:

- fundamental study of ice-pavement bonding
- pavement modification
- non-contact de-icing using acoustic or microwave energy
- high pressure liquid and sand blasting
- plow blade optimization
- development of standardized tests for de-icers.

While this research is at an early stage, it is hoped that fundamentally new approaches to de-icing will be developed. Approaches which show promise for successful implementation would then be incorporated in the MTO research program.

3/ Chemical De-icers

3.1/ Introduction

Chloride based de-icers have commonly been used in North America as ice disbonding or ice melting agents since the 1940's. Undesirable effects of these chemicals have been known since the 1960's and have led to the search for alternative de-icers.

This section reviews the present understanding of desirable and undesirable properties of chloride de-icers and of other proposed alternative chemicals.

Exhaustive searches for alternative de-icers have been conducted by the NCHRP [10], OECD [11], and the FHWA [12]. These studies ranked a large number of elements and compounds which have theoretical potential as de-icers, according to molecular weight and solubility. Elements which do not occur naturally in sufficient quantity were eliminated, as were those elements and compounds which are highly flammable, toxic, volatile or corrosive. Others were subjected to extensive study and experimentation, and a few have come into practical use. MTO has monitored this work closely and has conducted laboratory and field tests with most of the chemicals which are available in commercial quantities and may be suitable for use in the winter weather conditions prevailing in Ontario.

The properties, application practices and research into chemicals and abrasives which have been tested extensively, or used routinely for de-icing highways are reviewed below. De-icer Fact Sheets, which contain basic information on commercially available de-icers, are available from the Materials Office of the Research and Development Branch, MTO.

3.2/ Sodium Chloride

3.2.1/ Use of sodium chloride

Sodium chloride (NaCl) is the primary de-icing chemical used in Ontario and North America. Most of the salt is mined (rock salt), though some is produced by evaporation (solar salt). Under laboratory conditions, salt particles have been found to penetrate ice at a rate of roughly 1 cm per minute [7], varying slightly with temperature and grain size. As noted in Section 2, 1 gram will undercut and disbond about 58 cm^2 of ice once it penetrates to the pavement surface [7].

Salt is also added in small quantities, typically about 5 percent by mass, to stockpiles of sand used as abrasives. By dissolving with the microscopic water film adhered to the sand grains, salt prevents freezing of sand stockpiles and promotes adhesion of sand to the pavement surface.

The annual usage of sodium chloride de-icer in Ontario totals about 1.3 million tonnes, split approximately 54:46% between municipalities and MTO. The annual quantity used on provincial highways has increased slowly over the years and in 1988-89 was 620,000 tonnes [13]. The current price ranges from about $35 to $60 per tonne depending on quantities and location.

Rates at which salt is applied to the road vary according to weather and traffic conditions, but 130 kg per 2-lane km is effective under most conditions on Ontario highways [14]. This is slightly less than the rate recommended by the salt industry for temperatures just below freezing, and up to 40% less than industry recommendations for temperatures below -12°C [15]. This application rate means that each spreader, depending on capacity, can cover the distance shown in Table 1, and enable routes to be developed for each vehicle working from a patrol yard. MTO application practice is described further in Section 5.

Table 1/ Recommended rate of winter salt and sand application for Ontario highways

	Application Rate (kg/2-lane km)	2-lane Distance Covered (km)	
		Spreader Volume	
		4 m^3	6 m^3
Salt	130	35	56
Sand	570	12	19

Source: [14]

3.2.2/ Adverse effects of sodium chloride

While it is relatively inexpensive and effective, sodium chloride has several undesirable properties which have been the subject of recent research. They include:

- blow-off under cold temperature conditions,
- brine drainage through certain pavement surfaces, and
- adverse environmental effects

Blow-off occurs when salt is applied at cold temperatures and under strong wind or heavy traffic conditions. At such times, it blows or bounces off the road before it can begin melting into the ice, necessitating additional applications. Some experimentation has been undertaken in mixing additives with salt to promote melting under cold conditions and assist adhesion to the ice surface (Section 3.9).

Brine drainage through the pavement was identified as a problem on open-graded friction pavements, which are now being used on freeways to reduce noise and splash from tires. Salt grains penetrate into the large surface voids on this new type of pavement, allowing the de-icing brine to drain off through the pavement rather than act at the interface between the pavement and the surface ice. A laboratory study undertaken for MTO investigated two approaches to prevent the brine from draining through the pavement [16]. One approach involved coating the salt grains with a polymer to increase the viscosity of the brine and thus slow its drainage. However, brine retention was not significantly improved despite increases in viscosity of up to 10 times.

The second approach combined viscosity enhancement with encapsulation. A coating which swells on wetting was applied to salt grains, thus preventing them from working into the voids. Laboratory results indicated that this combined approach holds promise for preventing brine drainage, but additional work is needed to assess its feasibility on a large scale. Concurrently with the laboratory work, MTO patrols found that brine drainage was slowed after several applications of sand. In light of this phenomenon, laboratory studies were not continued.

Environmental effects of road salt have been recognized since the mid-1960's and led MTO to re-evaluate its application rates during the 1970's. This research is described in Section 5. Effects on natural and man-made environments have been documented and, while the latter are perhaps easier to quantify in dollar terms, research has examined both types of impacts.

Effects on the natural environment include deterioration of the quality of certain surface and groundwaters into which highway drainage flows, and damage to sensitive roadside plants [17]. As shown in Figure 4, de-icing salt can enter the natural environment via many pathways. If it enters a surface water or groundwater reservoir, it can affect both the taste and health properties of drinking water. Chloride affects the taste of water when its concentration reaches approximately 250 mg/L, while high sodium content has been suggested as a contributor to hypertension (high blood pressure) in individuals with a prior susceptibility to it [17]. The exact concentration at which sodium becomes potentially hazardous to such persons is not known. Sodium is an essential nutrient and 10 grams or more per day may be consumed by normal adults with no adverse effects [18]. The Ontario Ministry of the Environment suggests 20 mg/L as a cautionary limit in drinking water [18]. The medical research on which the relationship between salt intake and hypertension is based, and the degree to which salt is hazardous to public health, is currently under discussion [19]. Additional information on salt in groundwater is provided in Section 6.3.

De-icing salt is also implicated in damage to some types of roadside vegetation [17], promoting dessication and, in extreme cases, toxicity. It can occur when salt in solution is absorbed by the roots or splashed from the road onto the plant. Additional information on this effect is provided in Section 6.4.

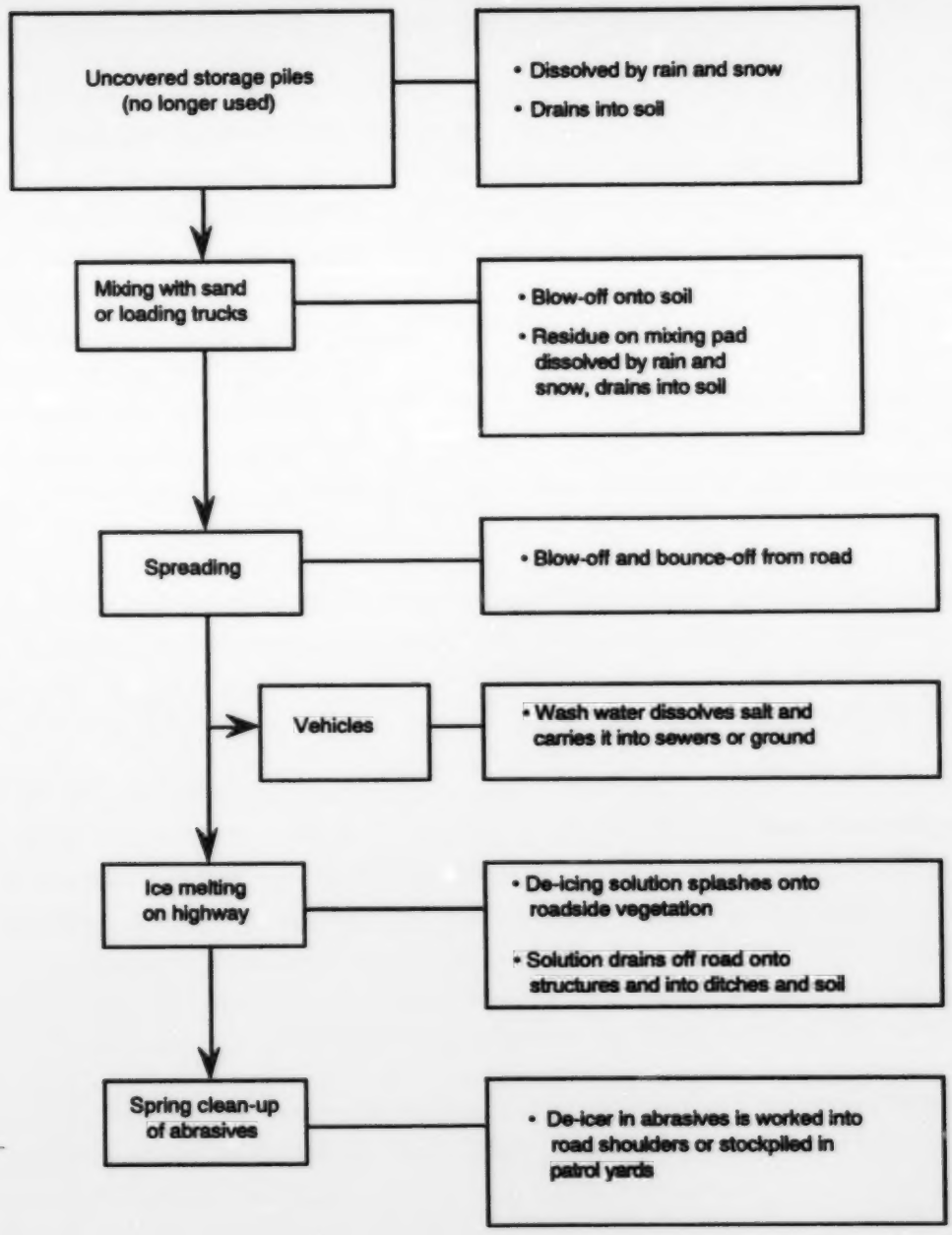


Figure 4/ De-icing chemical pathways into the environment

The chloride in de-icing salt affects the man-made environment by promoting corrosion in steel and other metals. It also contributes to the breakdown of concrete through freeze-thaw action, which causes scaling.

The corrosion of steel has a twofold effect on concrete structures. First, corrosion weakens the reinforcing steel which gives concrete structures, such as bridges and parking garages, much of their strength. Second, the chemical products of corrosion take up a larger volume than the original steel and this leads to spalling of the concrete. If chloride concentrations from past applications of salt exceed the threshold limit for corrosion at the steel interface, steel continues to corrode even if salt use is discontinued.

Over the past decade, accelerated structural deterioration has been recognized as a major problem for highway authorities throughout North America. A MTO study published in 1990 estimated that repair costs to provincial and municipal bridges, most of which are attributable to the effects of de-icing salt, are about $70 million annually [13]. Since the 1960's, research has been undertaken to find chemicals which can be applied with salt to reduce or stop the corrosion reaction [20]. To date, there is no evidence of their effectiveness in practice (see Section 6.6).

In the long term, it is believed that the costs from automobile and structural deterioration due to salt use will decrease as old units are rehabilitated or replaced, incorporating corrosion-resistant materials. This reduces the significance of the adverse effects of road salt and other chloride de-icers to the man-made environment, but not to the natural environment.

3.3/ Calcium Chloride

Calcium chloride ($CaCl_2$) has been promoted as an alternative or additive to sodium chloride on the basis of reduced overall use of chlorides, reduced overall cost, and better performance at low temperatures [21]. It has a lower eutectic point than salt (Figure 2), is deliquescent (absorbs moisture from the air until it turns into a liquid), and has an exothermic reaction with ice [20]. These properties help it to adhere to the road under colder conditions, dissolve more quickly, and melt ice at colder temperatures than rock salt.

Calcium chloride is available in pellet, flake, and liquid form. Suppliers have recommended its use both as a straight de-icer and as an additive to salt or sand. Application as an additive is described in Section 3.9.

Laboratory comparisons of the rates of melting and of undercutting of the ice surface (i.e., disbonding the ice from the pavement) indicate that at cold temperatures, calcium chloride is more effective than sodium chloride, per unit mass of chemical [7]. The tests showed that at -7°C over a period of 30 minutes, calcium chloride (in pellet form) melted 35% more ice per unit mass than did salt. Under the same test conditions, calcium chloride undercut 13% more ice bonded to a concrete pavement than did salt (Appendix A). Under warmer conditions (-7°C or warmer for calcium chloride in flake form and -4°C or warmer in pellet form),

calcium chloride was less effective than salt. The increased effectiveness at cold temperatures as compared to salt, plus a resulting reduction in quantity of material which would be blown off the road before melting begins, form the basis of the claim of reduced use of chlorides and reduced overall cost.

In all of the test cases, the use of calcium chloride resulted in a higher cost of de-icing than the use of salt, because of the much greater unit cost of calcium chloride. Calcium chloride would cost approximately 4.5 times more than salt to melt ice and 6 times more to disbond it.

Calcium chloride is not used as a straight de-icer by MTO, nor by most municipalities in Ontario [22]. Field trials by MTO and others indicate two reasons for this. Since it is deliquescent, the solution left on the road does not dry and maintains a wet, slippery driving surface [20]. In addition, snow which falls or drifts onto the highway will stick and may dilute the solution to the point that it refreezes into a sheet of ice [23].

The corrosive effects of calcium chloride on motor vehicles and concrete or steel structures are similar or worse than those of sodium chloride (see Section 3.2). The use of a corrosion inhibitor with calcium chloride has been proposed [21], but, as described in Section 6.6, inhibitors have not been proven effective in operational use.

Calcium chloride does not pose the potential health risks of rock salt because it does not contain the sodium ion. It does contain the chloride ion in larger proportion than sodium chloride, and smaller quantities would have to be used to reduce the effects of chlorides.

3.4/ Magnesium Chloride

Magnesium chloride ($MgCl_2$) was identified as a potential road de-icer by OECD [11] and FHWA [12]. It is promoted like calcium chloride, on the basis that it melts ice more quickly and at colder temperatures than salt, requires less chemical for equivalent de-icing (thereby reducing overall chloride input to the environment), and provides de-icing at a lower overall cost [21]. It is supplied in solid or liquid form for use as a straight de-icer and as an additive to salt and sand [21]. Its use as an additive is described in Section 3.9.

No controlled laboratory comparisons of the de-icing effectiveness of magnesium chloride with other de-icers are reported in the literature, but results from several field tests are available. A commercial de-icer consisting mainly of liquid magnesium chloride was tested on municipal roads in Richmond Hill, Ontario in 1988-89 [24]. It was applied at a rate of 600 L per 2-lane km, which is equivalent to 192 kg of dry chemical per 2-lane km (see Appendix B). In one test at -15° C, it melted a thin cover of dry, light snow within 1 hour. It was applied on ice at a second site at the same rate and temperature. Here it was less effective; it did not spread, but created pools of brine where it was applied on the surface. After 18 hours, the ice surface had become slushy, but hard ice remained underneath and was still bonded firmly to the road surface [25].

In both of these tests, the liquid did not dry. It left, in the former case, a wet pavement surface and in the latter, pools of liquid brine. De-icer which was splashed onto vehicles during these applications remained wet for a period of four days. These observations suggest that magnesium chloride, like calcium chloride, would be subject to dilution and re-freezing by subsequent snowfall or drifting.

The tendency for magnesium chloride solution to remain where it is spread rather than flow across the pavement was also noted in tests in Minnesota, where it was spread as a mix in sand at temperatures from -1 to -8°C [26].

If the de-icer is assumed effective at the application rate of 595 L per 2-lane km, recommended by the supplier [27], the cost of de-icing with magnesium chloride liquid would be almost 60 times that of salt, at the standard rate of 130 kg per 2-lane km (Appendix B). It is difficult to compare quantities and costs because magnesium chloride appears to be effective at melting, rather than disbonding the ice cover, and comparative data under controlled conditions are not available.

Laboratory tests by the manufacturer indicate that mild steel exposed to a 3% solution of magnesium chloride corrodes at approximately two thirds the rate of steel exposed to sodium chloride under the same conditions [27]. Magnesium chloride is marketed in combination with a lignosulphonate corrosion inhibitor, which is shown in the tests to further reduce the rate of corrosion by 50%. As described in Section 6.6, the degree to which laboratory tests of corrosion rate are applicable in a real-world situation is uncertain, and corrosion inhibiting additives have not been proven effective in field use.

3.5/ Calcium Magnesium Acetate

Calcium magnesium acetate (CMA) (see Appendix C for full chemical formula) was first recommended as an alternative to salt in a 1980 study by FHWA [12] and since then, has been the subject of extensive research in North America. It contains neither sodium nor chloride and does not have the undesirable environmental properties of chloride chemicals, while its performance as a de-icer is somewhat similar to salt (Figure 2).

Since investigations into CMA began, such physical characteristics as the ratio of calcium to magnesium, particle size, shape, colour and specific gravity have been adjusted several times [28]. A calcium : magnesium mole ratio of 3:7 was accepted as an interim standard by FHWA [29]. The current specification is listed in Appendix C.

3.5.1/ De-icing effectiveness of CMA

Comparison of the molecular weight of CMA and salt shows that CMA must be applied at a rate 1.7 times that of salt for equivalent de-icing.

However, field tests in a number of jurisdictions have shown that the de-icing performance of CMA differs in some respects from salt, and that application rates lower than the theoretical equivalent of salt can be used for comparable performance under some conditions.

Early trials were sponsored by the FHWA in Michigan and Washington [30, 31]. More recent U.S. trials were done in California, Wisconsin and Massachusettes [32, 33, 34]. Trials have been conducted independently in Canada in Ontario [28, 35, 36] and Alberta [37], and on a more limited basis by municipalities [24, 38].

Application rates in highway trials ranged from 1.1 to 1.7 times that of salt. Most of the trials showed CMA to have similar effectiveness to salt at temperatures down to -5° C, and to perform more slowly than salt at colder temperatures.

Two field trials have been conducted in Ontario; one in the vicinity of Burlington at the southwest end of Lake Ontario, and one near Owen Sound on the east side of Lake Huron. The Burlington trials were in conditions of relatively warm temperature, light snow and heavy traffic on a four-lane, divided highway. The Owen Sound trials were conducted on a rural, two-lane highway under cold temperature, heavy snow and light traffic conditions [35, 36]. Each of these trials included many winter storm events over two winter seasons.

In the Burlington trials, CMA application rates ranged from 145 to 220 kg per 2-lane km (1.4 to 1.7 times the standard salt application rate). No consistent differences in effectiveness were observed as a result of different application rates. CMA was effective at melting loose snow under most of the test conditions, which were usually at temperatures above -5° C, with light snow and heavy traffic.

The total quantity of material applied per km in these trials was 1.2 times the quantity of salt used on comparable sections of nearby highway in the first year, and 1.4 times the quantity in the second year. It was suggested that CMA residue remained on the pavement after many storms and initiated de-icing in subsequent ones, thus reducing the number of applications of CMA required. This residual effect was also noted in California, Wisconsin and Alberta [32, 33, 37].

In the Owen Sound trials, more severe winter conditions were experienced; the temperature at which CMA was applied was usually around -8° C, but was as low as -22° C. Material was often applied in conditions of severe blowing snow, freezing rain, and build-up of snow pack. Again, the effectiveness of CMA at melting loose snow or disbonding packed snow at temperatures down to approximately -5° C was similar to that of salt. At colder temperatures CMA took significantly longer to react than salt.

CMA dissolved with snow or ice to produce a slush, and the slush turned to liquid only at temperatures near 0° C or in the presence of frequent traffic. The slush was readily plowed from the road surface. The residual effect, noted in the Burlington trials, was also observed at Owen Sound, with the pavement remaining wet with de-

icer solution for several hours or days. Blowing snow stuck to the wet pavement and accumulated faster than it was melted, but did not freeze to the pavement and was plowed off easily [36].

The optimum application rate and conditions under which CMA can be considered an effective de-icer are still under discussion.

CMA has also been used to keep abrasive stockpiles from freezing and results of those trials are reported in Section 4.4.

3.5.2/ Cost of CMA

The cost of CMA is about 30 times that of salt, by mass (1990 figures). If an overall application rate of 1.5 times that of salt is assumed, the cost factor increases to 45 (Appendix B). Even if CMA were accepted as an environmentally benign and effective alternative to salt, the cost would be a substantial impediment to its widespread use.

Studies have been conducted to compare the cost of producing CMA with costs associated to the adverse effects of salt, and to investigate less expensive methods of producing CMA.

An Ontario study estimated that CMA would be an economic alternative to salt, if it eliminated all of the negative effects of sodium chloride, and could be produced for about $400 per tonne. This amount equates to the costs associated with automobile and structural corrosion, and damage to salt sensitive crops and drinking water supplies [39]. The study assumed a province-wide switch to CMA since de-icers and their effects are carried across jurisdictional boundaries. The break-even cost can only be approximate because the largest saving is in the reduced corrosion of automobiles. However, the corrosion resistance of automobiles has improved in recent years, making the use of historical data questionable. A similar study to compare the cost of CMA and salt was initiated by the U.S. National Academy of Sciences in 1990.

Given the $400 per tonne target, another study was undertaken to determine whether CMA could be produced at an affordable cost using advanced process technologies [40]. That study estimated that CMA can be produced on a large scale in the low $300 to $400 per tonne range using natural gas as the basic raw material. It could be produced at a slightly higher cost using municipal solid waste (MSW) as a feedstock. The costs were based on a plant capacity of 1 million tonnes per year. Such a plant would require a capital investment of approximately $1 billion. Additional study is required to prove the feasibility of gasification technology for the MSW process. The feasibility of using corn as the basic raw material to produce acetic acid by fermentation was also investigated and found to be more expensive and technologically difficult.

3.5.3/ Environmental Properties of CMA

CMA was developed as an environmentally benign alternative to chloride de-icers from the perspective of material corrosion, effects on roadside vegetation, and contamination of drinking water. Operational

experience with CMA has been insufficient to naturally identify possible environmental problems and therefore, laboratory studies have been conducted.

The FHWA [41] and MTO's Materials Research Office [42] have conducted laboratory tests to indicate the possible effects of CMA on automotive and highway infrastructure materials. The tests showed that the rate of corrosion of exposed steel and of scaling of concrete are both lower in solutions of CMA than in solutions of salt brine.

The corrosion potential of exposed steel is also reduced when CMA is added to a salt solution [42, 43]. This implies that CMA might be effective as an automotive corrosion inhibitor, subject to reservations about inhibitors as described in Section 6.6.

In tests conducted at MTO, steel samples immersed in a limewater solution simulated the environment in which corrosion of steel occurs in a concrete structure. The addition of CMA to the limewater solution did not reduce corrosion of the steel samples [44]. This implies that CMA will not be effective at reducing the rate of deterioration of existing highway structures or parking garages which have been saturated with chlorides, even if the use of chloride de-icers is discontinued. Additional study is needed to confirm these results.

Studies into the possible effects of CMA on the natural environment have focused on physical properties, chemical reactions and microbial activity in soil, terrestrial vegetation, surface water quality, and aquatic biota [45, 46]. The breakdown and possible interactions of CMA with soil constituents, groundwater, flora, and fauna are complex, and additional study is needed to determine whether or not the effects identified thus far are significant and whether there are any as yet unidentified effects.

Studies to date indicate that both the acetate and the cations (calcium and magnesium) in highway runoff from CMA are likely to be held by the soil, within a few metres of the highway. This could have two direct effects on the surrounding environment. First, movement of soil water tends to be improved by the presence of these cations. Second, plant growth could be affected. Tests show that CMA in low concentrations (4 g per kg of soil, corresponding to 10,000 ppm concentration in soil water at field moisture capacity) can retard plant growth. However, concentrations of this magnitude are exceedingly unlikely to occur within the root zone [46].

The calcium and magnesium could have indirect effects by displacing other cations such as iron, copper, zinc, and aluminum in roadside soils and granular material within about 3 m of the pavement. These cations could then be carried further from the road by groundwater, and re-adsorbed by soil particles beyond the influence of the CMA. Additional research is needed to determine whether this could significantly increase the transport of metals in groundwater [45].

The slow decomposition of CMA at low temperatures could result in its accumulation in roadside soils or receiving waters during winter months. The metabolism of this CMA by bacteria in springtime could result in

heavy blooms of algae. The subsequent breakdown of algae could reduce the availability of oxygen for aquatic animals [47]. This is unlikely to cause critical oxygen depletion in exposed ponds or soils, but could do so in ice-covered ponds [46] and additional research is needed to asses the significance of these effects.

In light of these possible negative effects of CMA, interim guidelines have been developed by the FHWA to restrict its application from sensitive areas [45].

3.6/ Formates

Formate compounds were first proposed as a highway de-icer in 1965 [48]. Most formates have a low molecular weight and a freezing point depression similar to salt (Figure 2). Of the forms investigated in 1965, sodium ($Na\ CH\ O_2$) and calcium ($Ca(CH\ O_2)_2$) were the most promising.

Sodium formate in solid form was tested on municipal roads in Ottawa at application rates ranging from 152 kg per 2-lane km at temperatures near 0° C to 568 kg per 2-lane km at temperatures colder than -10° C. Salt was applied under comparable conditions at rates of 168 to 576 kg per 2-lane km, respectively [38]. Sodium formate penetrated the ice under these conditions, but did not spread out on the pavement surface to disbond the ice. Instead, the de-icer solution formed a slushy windrow between vehicle tire tracks. The rate of reaction of sodium formate with snow and ice was about 50% that of salt under comparable conditions.

Subsequent to the Ottawa trials, a sample of the material used was tested and found to be contaminated with 531 ppm of chloride ions [44]. The chloride may have had a significant effect on the measured performance of the de-icer.

The cost of the commercial grade de-icer used in the tests was approximately 14 times the cost of de-icing salt, and the cost of a laboratory grade product which does not contain impurities, is significantly higher.

The environmental effects of formates are not well documented. Early tests showed calcium formate to cause spalling of concrete, while sodium formate did not have this effect [48]. The effect of sodium formate on corrosion of steel was tested by MTO using formate samples from the Ottawa trials [44]. These tests showed, contrary to the manufacturer's data, that corrosion rates in sodium formate solution could be twice as high as those in sodium chloride solution. Additional testing showed that four commercial brands of sodium formate contained chlorides in concentration ranging from 18 to 668 ppm, and that one brand also contained a proprietary corrosion inhibiting additive. These differences could explain the variation in corrosion rates measured [44].

Little information is available concerning potential effects of sodium formate on the natural environment. The sodium ion in formate would have similar effects on drinking water and roadside vegetation as the sodium ion in sodium chloride. Available data indicate that formate is toxic only at very high levels of concentration [49]. Formate can be metabolized by bacteria and therefore could have effects similar to those of CMA on the

availability of oxygen in roadside streams and ponds. Additional research is needed to show whether this effect is of environmental importance.

3.7/ Urea

Urea (NH_2 CO NH_2) is used as a standard de-icer on airport runways because it is not corrosive to aircraft materials [20]. However, it is less effective than salt and is restricted for use on highways in many areas because it has adverse effects on the natural environment.

Compared with salt, approximately twice as much urea by mass is required for de-icing, it reacts more slowly, and it is effective only at temperatures above about -10° C [50]. The unit cost of material is about 8 times that of salt (Appendix B).

The effects of urea on the natural environment preclude its use as a highway de-icer. After draining off the highway into roadside soils, it readily hydrolizes to carbon dioxide and ammonia in the presence of soil micro-organisms. Ammonia which does not break down further in the soil water may drain into streams and ponds, is highly toxic to fish and can be toxic to humans. Ammonia oxidizes in the soil to form nitrates, which promote growth of algae. Subsequent use of oxygen during decomposition of the algae can deplete the oxygen level below that needed to support aquatic life [51].

For these reasons, urea is not considered a viable alternative de-icer for highway use.

3.8/ Verglimit

Bridge decks which cool from both top and bottom surfaces, and road sections with insulated bases which prevent conduction of heat from the ground to the surface, are subject to more rapid ice formation than adjacent road surfaces. Localized ice formation is difficult and costly for maintenance crews to treat because it requires a knowledge of when icing conditions exist and a level of effort comparable to that required to treat the entire road surface. Verglimit, a patented compound, was developed to retard ice formation at susceptible locations in the temperature range of 0 to -5° C. As the temperature falls below this range, it is anticipated that the remainder of the road will freeze over and maintenance crews will be called out.

Verglimit consists mainly of encapsulated calcium chloride pellets which are incorporated into the bituminous surface when the road is paved. The capsules are gradually exposed and broken open year-round as the surface wears, allowing de-icer to be spread by vehicle tires.

The compound is added to asphalt paving at a rate of 5 to 7% by mass [52], which increases the cost of the paving by approximately 170%, not including the additional costs associated with mixing the pellets into the asphalt (Appendix D).

Verglimit has been installed at approximately 200 locations in North America, including 10 test sites on bridge decks on Ontario provincial highways [52]. In 5 of those cases, ice formation was retarded on the Verglimit surface as compared with the pre-installation condition or with nearby bridges on the same highway. In 4 other cases, no difference was reported and in 1 case, the Verglimit surface was more prone to ice formation than adjacent pavement. Where it was effective in retarding ice formation, it caused drifting snow to adhere to the pavement. This was also seen at a municipal installation, where a Verglimit pavement was prone to formation of glare ice at low temperatures [24].

In some cases, the effectiveness of Verglimit was reduced after 5 years, and measurements from pavement cores in those cases showed that the pellets had been dissolved from the upper 20 mm of pavement [52]. However, tests on an urban road in New York State showed Verglimit to remain effective at temperatures slightly below freezing for at least 7 years after installation [53]. Those tests also showed that the dry Verglimit pavement had a slightly lower coefficient of friction than standard pavement [53].

The environmental effects of Verglimit are identical to those of calcium chloride (except that the quantities of calcium chloride involved are very small).

Test results to date show that Verglimit can be effective at preventing early formation of ice in localized areas, but that it is not effective in every case. It is not possible to predict whether Verglimit will be effective at a particular site.

3.9/ Combinations of De-icing Chemicals

Each of the de-icers described above is effective under specific conditions or for a specific type of de-icing, and thus, each has limitations. Attempts have been made to use various chemicals in combination and thereby gain the benefits of each.

3.9.1/ Calcium chloride and salt

Calcium chloride in liquid or solid form has been promoted as an additive to sodium chloride since the late 1960's. The intended benefit from the use of calcium chloride is that it attracts moisture, which helps the sodium chloride adhere to the ice surface. It also increases the de-icer's contact area with the surrounding ice, promoting more rapid de-icing. One manufacturer predicts a net cost saving of up to 40% from decreased salt usage due to reduced blow-off and increased effectiveness at cold temperatures [54].

Twenty percent of Ontario municipalities of 15,000 or greater population use a calcium and salt mix for de-icing. While several municipalities report reduced salt usage, no objective comparisons with straight salt have been documented [22].

This combination has worked effectively for some municipalities, but was not successful in recent MTO tests where calcium chloride (in flake form) was mixed with salt [55]. In those tests, as well as earlier trials where liquid calcium was mixed with abrasives [23], rapid refreezing occurred as blowing snow adhered to the calcium-salt solution and diluted it until it refroze into glare ice.

In addition to a hazardous driving surface, problems were encountered with liquid calcium chloride leaching through the stockpile [23]. Recent tests by the manufacturer indicate that this may be avoided by using stronger solutions [56]. Storage problems have also been encountered with flake calcium chloride; moisture attracted by the flakes caused the formation of hard lumps which lodged in the spreader gate and could not be broken up by screening [55].

A commercial mixture of 20% flake calcium chloride and 80% salt costs approximately 3 times as much as salt (Appendix B) and, as already noted, any reduction in overall quantities used has never been documented. The environmental effects of the mixture are essentially the same as those for sodium and calcium chloride.

Effects on the natural environment would be lessened if the total quantities of sodium and chloride were reduced. However, calcium chloride is more corrosive to steel than is sodium chloride and this effect would be worsened.

3.9.2/ Magnesium chloride and salt

Magnesium chloride is commercially available as a mixture with rock salt at a ratio of 80% salt, 5% magnesium chloride, and 15% corrosion inhibitor. It is promoted as being effective down to -18°C when applied at the same rate as salt [27].

The intended benefit of the mixture is identical to that of a mixture of calcium chloride and salt. No data on the effectiveness of the mixture as compared with straight salt are reported in the literature. One field trial in the State of Washington reported refreezing one hour after application [57], confirming the reservations expressed in Section 3.4 about straight magnesium chloride. The product costs approximately 10 times as much as salt (Appendix B).

Environmental effects of the mixture are expected to be essentially the same as those for sodium and magnesium chloride.

3.9.3/ Calcium magnesium acetate and salt

A study by the State of Michigan reported that a mixture of salt and CMA could have de-icing capabilities similar to salt, while reducing the corrosion of steel to that of CMA solution. It would cost about 10 times as much as straight salt [43]. Reservations expressed in Section 3.5.2, concerning the corrosion inhibiting properties of CMA within existing concrete structures, are equally applicable when salt is present [44], suggesting that the CMA-salt mixture will not reduce corrosion.

The use of CMA as an inhibitor is also subject to the general reservations about inhibitors discussed in Section 6.6.

3.10/ Summary of De-icing Chemical Research

Most highway authorities are acutely aware of the adverse effects of road salt and many are actively involved in the search for an alternative. Several alternative chemicals are currently available, but they are more costly, less effective or have adverse effects equal to or greater than those linked with salt. Likewise, additives have been developed which reduce some of the negative effects of salt such as corrosion or damage to roadside plants, but they do not reduce all of the effects and have not been proven outside the laboratory.

Recent information suggests that CMA may have significantly fewer environmental effects than salt, and does not add sodium or chloride to the environment. Questions remain as to effectiveness at low temperatures, cost, effects on transport of metals in the soil and effects of its breakdown products which could deplete oxygen levels in roadside ponds.

4/ Abrasives

4.1/ Introduction

Abrasives such as sand or cinders are used to provide an immediate improvement in skid resistance on icy roads, particularly when temperatures are lower than the effective range of de-icing chemicals, or in freezing rain.

The exclusive use of abrasives as opposed to de-icing chemicals has been proposed in a number of municipalities (see Section 6.2) as a means of eliminating the adverse effects of de-icing chemicals. There are several reasons that this has not proven feasible in Ontario. First, abrasives provide traction for vehicle tires, but they do not assist in removing ice which is bonded to the pavement. Without a prior application of chemical de-icer to weaken this bond, the snow plow blade is not able to scrape the ice from the road and an uneven driving surface results [23]. Second, abrasives fill and block catch basins and, in urban areas, storm sewers. Even with the relatively restricted quantities used in conjunction with chemical de-icers, winter abrasives must be cleaned from catch basins in the spring. Greatly increased quantities might require periodic cleaning even during the winter. In addition, disposal of used highway abrasives may be a problem in jurisdictions where they are classed as a waste product (Section 5.3).

Finally, de-icing chemicals cannot be completely eliminated because they are required to prevent stockpile freezing. Small amounts of water are usually present between the grains of all abrasive materials and will cause them to freeze together in storage. To prevent this, to keep the material free-flowing as it is spread, and

to help it to stick to the icy pavement surface, a small amount of de-icing chemical must be mixed with the abrasives in the stockpile.

Research into winter abrasives has examined the skid resistance and susceptibility to blow-off of different abrasive materials, and the effectiveness of de-icing chemicals at reducing blow-off and preventing freezing of stockpiles.

4.2/ Particle Size to Maximize Skid Resistance and Minimize Blow-Off

Early investigations showed that abrasives should have the physical properties shown in Table 2 [58], with maximum diameter of about 1.3 cm, to minimize damage to vehicles and injury to pedestrians. The minimum particle size for effective skid resistance was shown to be 300 μm diameter (50 mesh) [58].

Table 2/ Desirable characteristics of winter abrasives

Characteristics	*Benefits*
Resistance to compression, crushing, impact, and grinding.	Resists degradation by traffic action.
Angular shape.	Prevents blow-off. Better skid resistance.
Dark colour.	Absorbs heat to melt itself into ice surface, reducing blow-off and increasing skid-resistance.
Uniform grain size.	Uniform spread pattern. Less likely to damage equipment.

Source: after [58]

Material and size standards for abrasives have long been established, but the price of standard materials has increased in some areas to the point that alternatives are being sought [59]. Two Ontario cities experimented with crushed aggregate ("winter grit") from which fines were washed. Ottawa reported reduced blow-off using material with diameter between 4 and 200 mesh (4.75 mm and 75 μm), while Richmond Hill reported no difference between winter grit and sand [24].

4.3/ Heated Sand

Prior to the widespread use of de-icing chemicals, sand used as an abrasive was heated to thaw it out for spreading and to improve adhesion to the road surface. This practice was abandoned in favour of stockpile de-icers in the 1950's.

Alaska conducted experiments in the 1980's to re-evaluate the feasibility of heating abrasive sand as an alternative to the use of salt [60]. It is based on the principle that hot sand will melt into the ice surface, refreeze and become bonded to it, creating a long-lasting, skid resistant surface.

Laboratory tests showed that heated sand spread on ice increased significantly the coefficient of friction as compared with sand at the same temperature as the ice, for ice temperatures below -1° C (30° F). At -1° C, the ice did not refreeze around the sand grains. However, the use of heated sand was not successful in field trials because the sand cooled below the melting point of the ice before it reached the ice surface.

4.4/ Abrasives Mixed with De-icing Chemicals

This section describes the use of abrasives mixed with various de-icing chemicals, usually in small quantities, for the purpose of preventing freezing of the stockpile and sometimes, in greater proportions, for the purpose of reducing blow-off.

4.4.1/ Sodium chloride with abrasives

Sodium chloride is commonly added to sand stockpiles to prevent the sand grains freezing together in hard lumps. It prevents the freezing of stockpiles by going into solution with interstitial water which surrounds the sand grains. The small quantity of de-icer solution thus formed also promotes adhesion of the sand to the ice surface.

Experience has shown that a mixture of 5% by mass of sodium chloride prevents freezing of stockpiles under weather conditions commonly experienced in Ontario. The ratio of salt to sand is sometimes increased under very cold conditions; however, no scientific research has been conducted to substantiate the increased ratios.

4.4.2/ Calcium chloride and sodium chloride with abrasives

Calcium chloride is added by several Ontario municipalities to the sand-sodium chloride mixture [22]. The objective of adding calcium chloride is to increase adhesion of the sand to the ice surface under temperature conditions in which sodium chloride is not effective. This is expected to reduce the number of applications of sand needed and thus to reduce the overall cost of ice control.

The municipalities which use the mixture report that it is effective, but they have not conducted controlled tests to show the cost savings. Field trials conducted by the New Brunswick Department of Transportation and MTO suggest that it is effective under some conditions, causes icing problems in others, and does not reduce costs.

A mixture of 75% sand, 23% sodium chloride and 2% calcium chloride (in liquid form) was used in New Brunswick trials [61]. The manufacturer predicted that cost savings of up to 41% would be realized as a result of a reduction in quantities of sand used over a winter.

A reduction in blow-off and a resulting reduction in sand application were observed. Cost savings were not realized; the saving due to reduction in quantities used did not equal increased expenditures, which were the result of the higher unit cost of calcium chloride as compared with salt, and the cost of installing equipment to handle the liquid de-icer [62].

Mixtures of 92% sand, 5% salt and 3% calcium chloride (in flake form), and of 90% sand, 8% salt and 2% calcium chloride (in liquid form) [63], and of 80% sand, 20% salt and 1% calcium chloride (in liquid form) [64] were tested in Ontario. The first mixture was tested on low volume urban roads and moderate volume highways at approximately -15° C. It was effective at promoting adhesion of sand to an icy road surface. The second test was conducted on a 2-lane highway at temperatures of -15 to -18° C. Here, no difference was seen in adhesion of the calcium-sodium chloride and sand mixture as compared with a 5% sodium chloride and 95% sand mixture. In the second test of sand and sodium chloride treated with liquid calcium chloride, the de-icer solution prevented drying of the pavement. The solution was diluted by drifting snow and refroze as glare ice.

That study also showed that the addition of calcium chloride did not improve adhesion qualities of the abrasive mix sufficiently that quantities could be reduced significantly, and did not result in an overall cost saving.

4.4.3/ CMA with abrasives

The environmental benefits of CMA as a de-icer would not be realized unless it were also substituted for salt to prevent freezing of sand stockpiles. Tests have therefore been conducted to ascertain the conditions under which it is effective at preventing freezing and promoting adhesion of sand to the road surface.

In one trial, CMA coated sand particles were spread on two urban roads and one 2-lane highway in northern Ontario [63]. At -19° C, blow-off of CMA coated particles was not reduced as compared with a sand-salt mixture. At -15° C, some sticking and penetration of the ice surface was seen, but the snow pack became slushy and the abrasive qualities of the sand were reduced.

The validity of these trials can be questioned because the CMA coated sand particles were much smaller than sand particles normally used as a winter abrasive. As well, subsequent tests have shown that CMA is not an effective de-icer at such temperatures and therefore would not prevent stockpile freezing or promote adhesion of sand. However, the coated sand trials are important in showing that care should be exercised in determining the ratio at which CMA is mixed with sand, because the abrasive qualities of sand may be reduced in the slush which is produced when CMA dissolves with ice.

CMA pellets were mixed with sand during four seasons of trials in southwestern Ontario [35]. In the first two seasons, no differences in storage qualities or effectiveness were seen between CMA-sand mixes of 14% and salt-sand mixes of 10 to 15%. In the third season, the ratio of CMA to sand was reduced to 5% and in the fourth year, to 2% as compared with salt-sand mixed at a 5% ratio. CMA prevented stockpile freezing in all cases. When

mixed at the 5% ratio, CMA appeared to absorb moisture, drying sand particles in the surrounding stockpile. This mixture of CMA and sand tended to blow off the road to a greater degree than the standard mixture of sand and salt, unless the road surface was wet [36].

The fourth season of trials included several tests in which the CMA-sand mix was sprayed with a 25% solution of liquid CMA as it was spread. This improved adhesion of the sand to the road surface [36].

In another test in Richmond Hill, no difference in adhesion was seen between 8% CMA-sand and 5% salt-sand applied on comparable sections of urban road at -6° C [65].

The tests indicate that CMA is effective at preventing the freezing of winter sand stockpiles. However, concerns remain as to its effect on adhesion of sand to the road surface unless it is pre-wetted or applied on wet surfaces, and the formation of slush by CMA pellets in the sand, with subsequent reduction in abrasive qualities of the sand as it is embedded in the slush.

4.4.4/ Magnesium chloride and sodium chloride with abrasives

Magnesium chloride has been tested as an additive to sodium chloride and sand. The magnesium chloride was supplied as a commercial product consisting of magnesium chloride, a corrosion inhibitor and water. The expected benefits were identical to those in trials of calcium chloride, that is, improved adhesion to the road surface at temperatures where salt is not effective.

In trials in Minnesota, magnesium chloride was added to salt and sand at a ratio of 5:5:90 [26]. The tests showed that blow-off was reduced as compared with a sand-salt mixture, however, they were conducted at temperatures between -1 and -8° C and did not show whether the same results would occur for temperatures below those at which salt is effective. Also, they did not show whether costs were reduced.

Trials were conducted at colder temperatures in Thunder Bay [63]. In these tests, magnesium chloride coated salt was mixed in sand. No differences in adhesion were seen on comparable sections of road using the magnesium chloride-salt and straight salt-sand mix.

The tests conducted thus far show that adhesion of abrasive mixtures may be improved by addition of magnesium chloride within the temperature range at which salt is used. However, they show neither a cost saving resulting from improved adhesion at these temperatures, nor improved adhesion at temperatures colder than the effective range of sodium chloride.

4.4.5/ Sodium formate with abrasives

Sodium formate has been used to prevent freezing of sand stockpiles in one trial in Minnesota [26]. No other tests have been reported in the literature. In the Minnesota trial, it was mixed with sand at ratios of 5% and 20%, and used at temperatures ranging from -2 to -9° C.

The formate-sand mixture hardened in storage, and when loaded into the spreader box, it absorbed moisture and became sticky. This prevented the sand from discharging through the spreader chute.

These results suggest that sodium formate is not a practical alternative to salt as a stockpile de-icer.

4.5/ Summary of Abrasives Research

Recent research on abrasives has been directed toward preventing blow-off to reduce the total quantities used, and to maintaining a skid resistant driving surface.

De-icing chemicals which have been proposed as alternatives to salt have also been proposed to prevent the freezing of abrasives in stockpiles. The tests to date do not show that any of the alternative chemicals perform better than salt for highway applications. Calcium and magnesium chloride have been used in some areas as an additive to salt in abrasives in urban applications and appear to reduce blow-off as compared with the standard salt and abrasive mixtures; however, no quantitative measure of the savings accrued has been reported.

5/ De-Icing Practices at MTO

5.1/ Introduction

Standard practices for winter maintenance are documented in MTO Operating Instruction M-700 [14]. The Instruction specifies levels of snow and ice removal according to roadway traffic volume using a four-tiered system. The levels are differentiated according to the amount of bare pavement maintained and the time in which ice and snow must be removed following a storm. These levels are described in detail in Maintenance Quality Standard M-700-1 and are summarized in Table 3.

The purpose of the standards is to ensure a consistent driving surface for a particular class of road and weather condition, so that driving habits can be adjusted to suit the situation. This approach also assists in budgeting for winter maintenance and measuring the effectiveness of local maintenance operations. Recommended snow and ice control treatments for each service level are summarized in Table 4 [14].

Table 3/ Levels of service for winter maintenance

Level of Service		*Highway Type and W.A.D.T.*[1]	*M.A.A.*[2] *(cm)*	*Percent Storms Serviced*[3]
Class	*Type*			
1A	Bare Pavement	Multi-Lane Divided, and others with W.A.D.T. over 10,000	2.5	98
1B	Bare Pavement	Trans Canada System, and others with W.A.D.T. 2000-9999 (south) and 1500-9999 (north)	2.5	95
2	Bare Pavement	1000-1999 (south 800-1499 (north)	4.0	95
3	Centre Bare Pavement	500-999 (south) 400-799 (north)	5.0	90
4	Snow Packed	under 500 (south) under 400 (north)	7.0	75

1. *W.A.D.T. - Winter Average Daily Traffic*

2. *M.A.A. - Maximum allowable accumulation. The maximum depth of snow in centimetres permitted to accumulate on the road.*

3. *Percent Storms Serviced - The percentage of storms during which no more than the maximum allowable snow accumulation is permitted to accumulate on the road.*

Source: [66]

Recommended Treatments for Class I and II Bare Pavement and Class III Centre Bare Level of Service

	Temperature Range °C	Type of Precipitation	Road Condition	Activity	Recommended Treatment 4/		
					Beginning of Storm	During Storm/1	After Storm/2
1	Below -18°	Dry Snow	No Packing Dry Pavement	Plowing	After 2 cm of snow accumulation	Continuously	Bare pvt/wing shlds/clean up
				Sanding	If slippery	Follow after plowing, if slippery	Slippery sections only
				Salting	No	No	If temp. rising, to bare or assist in baring pvt.
2	-18° to -12°	Dry Snow	No Packing Dry Pavement	Plowing	After 2 cm of snow accumulation	Continuously	Bare pvt/wing shlds/clean up
				Sanding	If slippery	No	Slippery Sections only
				Salting	No	No	If temperature rising, to bare or assist in baring pavement
3	-18° to -12°	Dry Snow	Packing	Plowing	If temp rising, after salting If temp falling, after 2 cm accumulation	Continuously	Bare pvt/wing shlds/clean up
				Sanding	If temp falling, if slippery	If temp falling, follow after plowing, if slippery	If temp falling, slippery sections
				Salting	If temp rising before 0.5 cm accumulation	If temp rising, as necessary after plowing	If temp. rising, to bare or assist in baring pvt.
4	-12° to -7°	Dry Snow	No Packing	Plowing	After 2 cm of snow accumulation	Continuously	Bare pvt/wing shlds/clean up
				Sanding	If temp. falling, if slippery	Follow after plowing, if slippery	Slippery sections only
				Salting	No	No	If temp. rising, to bare or assist in baring pavt.
5	-12° to -7°	Dry Snow	Packing	Plowing	0.5h after salting	Continuously	Bare pvt/wing shlds/clean up
				Sanding	No	Follow after plowing, if slippery	slippery sections only
				Salting	If temp rising, before 0.5 cm of snow accumulates	As necessary after plowing, to assist plowing	If temp rising, to bare or assist in baring pavt.
6	Above -7°	Wet Snow	Packing Wet Pavement	Plowing	0.5h after salting	Continuously	Bare pvt/wing shlds/clean up
				Sanding	No	Follow after plowing, if slippery	Slippery sections only
				Salting	Before 0.5 cm of snow accumulates	As necessary after plowing	To bare or assist in baring pavt.
7	Above -7°	Sleet or FreezingRain	Possible Icing Wet Pavement	Plowing	No	No	Remove any slush
				Sanding	No	Yes	Slippery sections only
				Salting	When icing starts	Yes	Slippery sections only

1. During storm conditions plowing should be undertaken to ensure that the accumulation of snow on the road surface does not exceed 2.5 cm for Class I, 4 cm for Class II, and 5 cm for Class III Service Levels.
2. After the storm , plowing should continue to achieve bare pavement within 24 h for Class I and II Service Levels. Plowing after the storm should be done to achieve baring of the centre 2.5 m of pavement within 24 h, whenever possible, for Class III Service Levels, and then bared full width when favourable weather prevails.
3. Winging back shoulders should usually be done only once after the storm.
4. Recommended treatment for various conditions shown on this chart should be used in most cases. However, unusual circumstances may necessitate departure from the recommended treatment.
5. Temperature rising means temperature to remain in or rise above temperature range.
6. Temperature falling means temperature to remain in or fall below temperature range.

Table 4/ MTO recommended treatments for removing snow and ice from highways

Research and Development Branch

Class IV Snow Packed Level of Service

	Temperature Range	Type of Precipitation	Road Condition	Activity	Recommended Treatment 1/		
					Beginning of Storm	During Storm 2/	After Storm 3/
1.	Any Temperature	Dry or Wet Snow	Road, Snow Packed	Plowing	Continuously (maintain snow pack)		Wing back shoulders / scarify slippery sections / clean-up
				Sanding	No	On hills, curves and other hazardous locations	
				Salting	No	No	No (gravel surface) Yes (paved surface) if -12°C and rising
2	Any Temperature	Sleet or Freezing Rain	Possible Icing	Plowing	No	No	Scarify slippery sections
				Sanding	No	Slippery sections	
				Salting	No	No	No (gravel surface) Yes (paved surface) if -12°C and rising
3.	Any Temperature After Storm	No Precipitation	Drifting	Plowing			Continuously (maintain snow pack)
				Sanding			Slippery Sections
				Salting			No

1) Recommended treatment for various conditions shown on this chart should be used in most cases. However, unusual circumstances may necessitate departure from the recommended treatment.
2) During storm conditions, plowing should be continuous to ensure that the accumulation of new snow does not exceed 7 cm.
3) Winging back shoulder should usually be done only once after the storm.

Table 4/ MTO recommended treatments for removing snow and ice from highways (continued)

Research and Development Branch

5.2/ Chemical De-icing

The application of de-icing salt is described in Maintenance Operating Instruction M-700-C, reproduced in Appendix E.

Sodium chloride is applied to snow or ice to prevent its adhesion to the pavement. It should not be applied to dry snow which is not sticking to the pavement, nor under very cold temperatures where it would not be effective. It is normally applied at temperatures of -12°C or warmer, but in bright sunshine or heavy traffic conditions, it can be effective down to -18°C. It should not be used in anticipation of a storm because of wastage due to blow-off or errors in forecasting, but can be applied soon after snow begins to fall in order to begin dissolving before snow or ice become bonded to the pavement. The salted road should not be plowed for at least 30 minutes after salt application, to allow the brine time to penetrate to the road surface.

Salt is applied in a narrow (30 cm) windrow along the crown of the road, or at the high point of super-elevated sections so that the brine will spread down-gradient across the road. On open-friction pavements or those with no crossfall where these processes will not be effective, a spinner should be used to distribute it uniformly.

The recommended rate of application in Ontario is 130 kg per 2-lane km. This was published as an MTO standard in 1973 [66] and was confirmed with comparative tests at rates from 100 to 185 kg, in the late 1970's [23]. This rate provides effective de-icing under most weather conditions experienced in the province and minimizes the total amount of salt used.

In some cases, one heavier application may result in lower total salt use than two or three lighter ones, and actual applications may therefore be varied according to weather conditions, up to a maximum of 170 kg per 2-lane km.

5.3/ Abrasives

Sand is applied on slippery snow or ice surfaces when the temperature is too low for salt to be effective, usually below -12°C. The standard rate as described in Standard M-700-C, is 570 kg per 2-lane km, applied in a 2 to 2.5 m swath on the crown of the road. It is spread across the driving lanes by traffic.

Sand is normally mixed with salt at 5% by weight to prevent freezing of the stockpile and maintain free-flow through the spreader. At the standard sanding rate, this applies 28.5 kg of salt per 2-lane km of pavement. The de-icer can be increased somewhat to improve adherence of the abrasive to the road, but any amount of salt greater than 5% is considered a straight de-icer application for accounting purposes.

Excess sanding should be avoided because it blocks catch basins and storm sewers and must be removed at the end of the winter. Disposal of used roadsweeping materials is regulated by the Ministry of the Environment

(MOE). Generally, winter abrasives from low traffic (primarily non-urban) highways can be reused as construction or fill material on-site, or stockpiled for later reuse so long as this is not within a specified distance of water courses or water supplies [67]. Alternatively, it can be disposed of as fill on non-residential and non-agricultural land with the same restrictions as above. Material from high traffic highways must be disposed of as (non-hazardous) waste, at an MOE approved waste management site, for which MOE approvals must be obtained.

The use of increased ratios of salt to sand beyond the quantity necessary to prevent stockpile freezing and assist in the adhesion of sand to the road is not recommended under normal circumstances. Higher ratios neither improve the abrasive qualities of sand nor the de-icing qualities of salt.

The inefficiency of high salt to sand ratios was demonstrated in a study in the Toronto area. Adjacent sections of freeway were treated either exclusively with salt or with the standard practices using salt or salt-abrasive mixtures. The mixtures varied between 5 and 15% salt at the discretion of the patrol supervisor, and the experiment was conducted only at temperatures where salt is effective [68].

Over one winter season, similar levels of service were maintained in the salt and salt-abrasive sections. The straight salt sections were serviced with a slight increase in salt usage and a large reduction in sand usage as compared with the sections in which either salt or salt-abrasive mixes were used. Fewer applications were needed in the straight salt sections, so material spreading costs were reduced.

6/ Mitigation of Adverse Effects of De-icers

6.1/ Introduction

Several pathways exist by which de-icing chemicals can enter the environment (Figure 4). They provide a variety of possible means to mitigate the adverse effects of salt, including; reduction in application, protection of sensitive areas of the environment, and rehabilitation of affected objects.

6.2/ No Salt Policy

Beginning as early as 1970, about two dozen municipalities in North America have, at times, declared a "no salt" or "reduced salt" policy in winter road maintenance. The extent of these policies has ranged from a total ban on salt usage, to restrictions on usage in sensitive areas, to substitution of other de-icers for sodium chloride in a continuing de-icing program. They typically have met with a high level of public approval at the outset, but none of the total salt bans has lasted more than one winter season [69].

MTO experimented with a "plow and sand only, do not salt" policy at selected sites in the late 1970's [23]. The trial resulted in unsafe conditions and was quickly terminated.

In other cases, the use of salt was replaced by increased use of abrasives. As noted in Section 4.1, this creates an uneven driving surface which is unsafe for high speed travel, and as well, it increases clean-up costs in the spring. In some cases, the quantity of de-icing chemical (sodium or calcium chloride) mixed in the abrasive stockpiles was increased until it almost equalled the quantities which would have been applied as straight de-icer.

6.3/ Groundwater Rehabilitation

The total annual cost to the public of groundwater contamination from road salt in Ontario has been estimated at $5.9 million [13], including about $1.5 million in legal claims to MTO alone [70]. One possible solution to this problem is to rehabilitate the affected water source.

MTO, in cooperation with MOE and Environment Canada, conducted an experiment at a patrol yard north of Toronto, to assess the feasibility of rehabilitating groundwater contaminated by road salt [71].

Salt was stockpiled in the open at this site from 1956 until 1976, at which time a covered storage facility was built. Nearby residents first complained of salty well water in the late 1970's. Measurements taken in 1985 indicated that a contaminated plume with average chloride content of about 10,000 mg/L had accumulated. Preliminary estimates put the plume volume at 76 million litres and the salt content at 790 tonnes [71]. Natural chloride concentration in groundwater varies widely, and ranged from 10 to 1000 ppm in one study near the patrol yard [72].

This site was selected for a pilot project to test the feasibility of groundwater rehabilitation using a process known as reverse osmosis (RO). This process has long been used on ships for purifying seawater for drinking purposes. The process used by MTO is illustrated schematically in Figure 5 and involved pumping contaminated water out of the ground and then forcing it, at high pressure, through a semi-permeable membrane to remove the salt. Clean filtrate was then returned to the ground through an infiltration ditch.

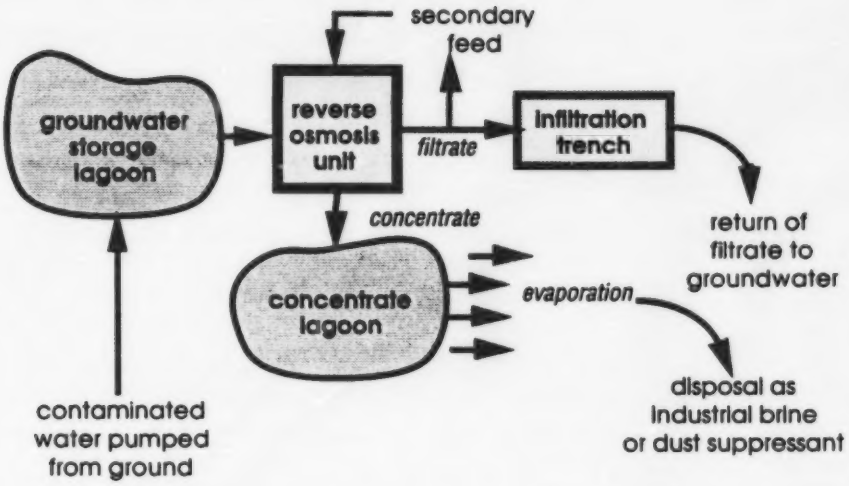


Figure 5/ Reverse osmosis process for groundwater rehabilitation

Two different RO systems were tested, one with an average filtration rate of 1230 L/h and another with a rate of 5000 L/h, although at a lower efficiency. In total, approximately 5.7 million litres of groundwater were processed over two summer seasons, treating 7.5% of the estimated plume volume. It removed 18.6 tonnes, or about 2.3% of the total salt mass in the plume.

The average operating and leasing cost was $7500 per tonne of sodium chloride removed from the ground. Based on the above figures, a total clean-up of this site would cost about $6 million and take three years to complete.

The experiment showed that it is technically feasible to rehabilitate salt contaminated groundwater using the RO process, but the cost of $7500 per tonne may be prohibitive.

6.4/ Protectants for Vegetation

Research has shown a variety of means by which salt brine, splashed or sprayed from the roadside, may be harmful to plants [17]. These include; browning, burning, die-back of buds, leaves or twigs, and reduced growth and hardiness. The annual cost of damage to vegetation in Ontario has been estimated at $2.8 million, principally to sensitive fruit orchards located adjacent to highways. An investigation was conducted to determine whether salt-spray injury to trees can be reduced by the use of film-forming protectants.

Protectants coat the plant surface with a physical barrier intended to prevent dessication, winter injury, and fungal infections. Eighteen different protectants were tested including silicone, wax emulsions, pine oil

emulsions, organic and acrylic polymer emulsions, tall oil emulsion and polyvinyl acetate, polyvinyl alcohol, and hydrocarbon resins [73]. Both natural and artificial plots and spray conditions were used.

The study showed a wide variation in protectant effectiveness according to plant type, experimental conditions, and method of evaluation. Such protectants hold promise as a means of reducing the effects of road salt on roadside plants, but more research is required before their use can be recommended on a large scale.

6.5/ Structural Protection

As noted in Section 3.2, the rate of corrosion and deterioration of steel and concrete in bridges, parking garages, and similar structures can be increased by road salt brine. The cost of added deterioration due to salt has been estimated at $216 million annually for the Province of Ontario [13].

This problem has been recognized since the early 1970's and a number of mitigative techniques have been developed [74, 75]. Some of these, including improved concrete, increased depth of cover to reinforcing steel, epoxy coating of reinforcing bars, and the use of waterproofing membranes on bridge decks, are now commonly used in new construction and in structural rehabilitation. Cathodic protection, which involves applying an electrical current to steel in the structure, has been used on an experimental basis since the mid 1970's and is now emerging as a successful and practical alternative for existing structures.

Another method, electrochemical removal of chloride from concrete, is at an early experimental stage [76].

In the future, the effective use of these anti-corrosion treatments during the rehabilitation or construction of steel and concrete structures, will substantially reduce the costs of structural corrosion due to de-icing salt usage.

6.6/ Corrosion Inhibitors

A number of chemical products have been developed which, when in solution with salt, reduce the rate of corrosion of steel as compared with the rate in salt brine alone. Testing of such chemicals began in the 1940's and continues today. Among those tested are chromates, polyphosphates, and lignosulphonates [57, 77].

Several inhibitors have proven effective under laboratory conditions in which the concentration of the inhibitor is constant [26, 57]. However, no tests have yet shown them to be effective under operational conditions which are very different from those in the laboratory. The following concerns must be addressed when testing the effectiveness of a corrosion inhibitor:

1) The effect of dilution with time, i.e. as the de-icer goes into solution, the concentration of the inhibitor is reduced very rapidly.

2) The possibility of separation of the inhibitor from the de-icer because of different solubility rates. For solids, the inhibitor may only be coated on the particle surfaces and will dissolve first.

3) The long-term effectiveness of the inhibitor, e.g. on the corrosion of vehicles and embedded reinforcement in the summer months when corrosion rates are highest.

Corrosion-inhibiting coatings or additives to chloride de-icers which may be effective in laboratory tests, cannot be recommended for use until these issues are resolved.

7/ Legal and Statutory Issues

7.1/ Claims and Litigation

In spite of industry-wide improvement in salt storage and spreading practices over the past three decades, road salt continues to adversely affect the environment. Maintenance authorities are under continuing pressure to compensate individuals for interference with the use of their property due to effects of road salt. The Claims Section of MTO's Office of Legal Services receives approximately 100 claims each year from individuals whose drinking water supplies have allegedly been contaminated by road salt [70].

High levels of chloride, typically cited as proof of road salt contamination, are not always the result of road salt usage. An investigation was carried out into methods by which different sources of chloride can be discriminated [78]. It showed that the ratio of iodide (a form of iodine) in chlorides derived from road salt is different from the ratio in chlorides derived from other sources such as natural bedrock and soil formations, or agricultural chemicals. The ratio of iodide can therefore be useful in identifying spurious claims in which the source of chlorides is not de-icing salt.

Not all claims go to litigation, and MTO pays out roughly $1.5 million annually in legitimate claims for property damage due to the effects of road salt. Methods of compensation include provision of alternative water supplies, and in extreme cases where the use of a property has been severely impaired, purchase of the property [70].

Legal action can be brought against a highway maintenance authority through two avenues: common law and statute law [17]. Litigation through common law involves such charges as negligence, trespass, or public nuisance and is the more serious of the two avenues. A frequently cited precedent for cases involving property damage due to de-icing chemicals is an 1868 action in English common law known as Rylands vs Fletcher [79]. In that case, Fletcher dammed a river to create a reservoir on his property. Unknown to him, the reservoir leaked into and flooded disused mines on Rylands' adjoining property. Fletcher was successfully sued on the grounds

that he allowed a foreign substance on his property to escape, causing a nuisance. Rylands and Fletcher has been referred to in modern cases where stored materials such as road salt have affected adjacent properties.

Examples of litigation in common law for specific effects of road salt are discussed in Sections 7.2 and 7.3.

Ontario statutes relevant to the environmental effects of road salt include the Environmental Protection Act (EPA) and the Ontario Water Resources Act (OWRA). The OWRA is the primary Provincial statute prohibiting water pollution. Through the proposed Municipal Industrial Strategy for Abatement (MISA) and the Sewer Use Bylaw, OWRA is expected to set stringent standards for pollutants in any discharge of water. Because of its importance to highway safety, salt, when applied to the road, is exempt as a contaminant under the EPA. An exemption under the OWRA is currently under discussion. Salt brine draining from a patrol yard or a storage pile is not exempt.

7.2/ Orchards and Vegetation

Insight concerning liability for road salt effects on farm crops in Ontario is provided by the cases of Schenck et al v. the Queen and Rockeby v. the Queen [80]. Schenck and Rockeby each brought a case against the Province, (in 1972 and 1978, respectively) for damages suffered to their fruit trees due to salt brine splashed from adjacent highways. The cases were tried together in the Supreme Court of Ontario in 1981 and found against the Province. An appeal to the Ontario Court of Appeal was also decided in favour of the claimants. The basis for the judgement was as follows [80]:

> "...no cause of action in negligence could here be sustained against the provincial government. There was no evidence that the quantities of salt used here were greater than was necessary for the essential task of keeping these highways free of ice-hazards; not that the Ministry's maintenance standards were unreasonable; not that the salt was applied in a negligent way. The use of salt, in preference to other, alternative de-icing chemicals, on the roads beside these highways, could not in itself be considered negligent.
>
> And while it had been suggested the defendants were negligent in failing to provide roadside barriers of some kind, there was insufficient evidence that such measures would materially have improved the situation.
>
> No cause of action could here be maintained under the rule in Rylands v. Fletcher, since the use of salt as a de-icing agent on Ontario roads was in no sense a "non-natural use" of land, nor was salt an inherently dangerous substance such as should properly attract the operation of the strict liability rule; especially where, as here, the activity or condition complained of was for the general benefit of the community.

> The actions in nuisance, however, must succeed. Such actions required a Court to balance the plaintiffs' claim to the undisturbed use and enjoyment of their land against the undoubtedly necessary and important activity of maintaining highway safety, for the general public good. Where, as here, actual physical damage of a substantial kind was being visited upon the plaintiffs' lands, and where, as here, the damage was not attributable to any ultra-sensitive use of those lands, the plaintiffs should not be compelled to suffer their losses without compensation. If, as it seemed, such damage was unavoidably incidental to the use of salt in winter highway maintenance, fairness demanded that the loss be borne by the public generally, and not by the plaintiffs alone."

The Ministry's road salting practices were seen to be neither excessive nor incorrect, but the ruling was seen as a method by which the cost of adverse effects could be shared among all beneficiaries of highway de-icing.

The ruling of the Ontario court was appealed to the Supreme Court of Canada. That appeal was dismissed in 1987 and the case was referred back to the Ontario Supreme Court for assessment of damages.

7.3/ Concrete Structures

The effects of de-icing salt on concrete and steel structures are now well recognized, and several large cases have been brought to trial to assess liability for increased structural deterioration due to salt [81, 82]. These involve public and private parking garages which the plaintiffs claim were subject to accelerated structural deterioration, due to de-icing salt tracked in from public roads.

Under dispute is whether the responsibility to take adequate precautions against the effects of de-icing salt, known to be used on Ontario roads, rests with the building designers, builders or managers, or with the road maintenance authorities who use salt and would then be liable for consequential damages.

In one such case, a building designer was held not liable provided he practiced state-of-the-art engineering at the time of construction [81]. While the effects of salt corrosion on concrete structures have been known for years, design provisions recognizing this fact were not included in the Ontario Building Code until 1988. Other cases are pending.

8/ Summary and Conclusions

Sodium chloride continues to be the most commonly used chemical de-icer. It is effective at winter temperatures typical in the Province of Ontario, and is inexpensive compared with most other de-icers.

The adverse effects of salt on vegetation, groundwater, motor vehicles, and concrete and steel structures are recognized by MTO and other road maintenance authorities. Several approaches have been developed to mitigate these undesirable effects.

The most successful mitigation of these effects has been in the development of more corrosion-resistant vehicles and new design codes to make concrete and steel structures less susceptible to salt-induced corrosion. Programs to reduce salt usage to the minimum required for safe driving conditions have also been successful. Chemical additives which are intended to inhibit the corrosive effects of chloride de-icers have been developed, but serious questions remain as to their effectiveness under operational conditions when applied with the de-icer.

Further work is needed to assess the feasibility of protectants for roadside vegetation, and rehabilitation of contaminated groundwater.

The ultimate solution is to find an alternative de-icing chemical which is as effective as rock salt but does not have adverse environmental effects. Currently only the chemical CMA holds promise of meeting these requirements. However, questions remain as to its effectiveness at low temperatures and whether it can be produced at an affordable cost.

MTO is committed to finding an effective and environmentally benign de-icer for use in Ontario, through a continuing de-icer research program.

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Appendices

Appendix A

Comparative Amounts of De-Icers to Melt and Disbond 3 mm x 2-lane Ice Sheet

1. Melting by Sodium Chloride in Laboratory Test:
   In 30 minutes at -7°C, NaCl melts 2.9 kg of ice/kg salt [6]
   Mass of a 3 mm, 2-lane km of ice:

Assume mass of ice:	900 kg/m^3
Volume of ice:	7300 x .003 = 21.9 m^3
	900 x 21.9 = 19710 kg

   Mass of salt required: 19710/2.9 = 6796 kg

2. Undercutting by Sodium Chloride in Laboratory Tests:
   In 30 minutes at -6.7°C, NaCl undercuts 58 cm^2/g [7]
   To undercut a 2-lane km:

   $$\frac{7300}{.0058} = 1258620.7 \text{ g}$$
   $$= .1259 \text{ kg}$$

3. Disbonding by Sodium Chloride in Practice:
   In approximately 30 minutes at 0°C to -12°C, 130 kg NaCl [14]
   disbonds 2-lane km of highway

4. Melting by Calcium Chloride in Laboratory Tests:
   In 30 minutes at -7°C, $CaCl_2$ melts 6.7 kg of ice/kg [6]
   Mass of a 3 mm, 2-lane km of ice: 19710 kg
   Mass of $CaCl_2$ required: 19710/6.7 = 2942 kg

5. Undercutting by Calcium Chloride in Laboratory Tests:
   In 30 minutes at -6.7°C, $CaCl_2$ undercuts 66 cm^2/g [7]
   To undercut a 2-lane km:

   $$\frac{7300}{.0066} = 110600 \text{ g}$$
   $$= 1106 \text{ kg}$$

NOTE: A 2-lane km = 3.65 m x 1000 m x 2 lanes
= 7300 m^2

Appendix B

Comparative Costs of De-icing Chemicals

De-icer	Cost Per Unit	Source	Application Rate	Source	Cost Per 2-Lane Km	Comments
sodium chloride	$35/tonne	13	130 kg/2-lane km	14	$ 4.55	MTO standard
calcium chloride	$240/tonne (flake)		not applied straight			
80:20 salt:calcium	$100/tonne	55	130 kg/2-lane km	55	$13.00	"PM-20"
magnesium chloride	$0.55/litre	13	2 US gal/1000 ft^2	13, 24	$327.00	"Freezeguard + PCI"
magnesium salt mix	$400/tonne	25	130 kg/2-lane km	25	$ 52.00	"Qwiksalt + PCI"
CMA	$1100/tonne	13	195 kg/2-lane km 156-182 kg/2-lane km	35	$214.50	Single applic. Winter total
sodium formate	$480/tonne	38	130 kg/2-lane km	38	$62.00	
urea	$280/tonne	65	208 kg/2-lane km	20	$58.24	
Verglimit	$1345/tonne	52	50-70 /kg/tonne asphalt	52	+additional mixing	see (24)

Appendix C

CMA Specifications

Production grade CMA shall have the following properties:

1. Shape - CMA shall have an approximately isodimensional particle shape.

2. Size and Gradation - CMA shall have a size gradation with a minimum of 90% passing screen size 3.33 m (sieve 6) and a maximum of 10% passing screen size 2.36 mm (sieve 8).

3. pH - An aqueous solution of 10% CMA shall have a pH of 8-9.

4. De-icing Ability - Melts ice at 25°F producing 1 mL of water/h/sq ft over a 24 h period under laboratory conditions when applied at 7.6 g/sq ft of ice.

5. Calcium, magnesium, carbon, and hydrogen analysis conforming to:

   $Ca_xMg_y(C_2H_3O_2)_4 \cdot zH_2O$

   $x = 0.6 - 0.8$

   $y = 1.2 - 1.4$

   $z = 0 - 3$

6. Calcium/Magnesium - The Ca/Mg mole ratio of water soluble product shall be between 0.60 and 0.70.

7. Insoluble Material - The percent of water insolubles shall be $\leq$ 3%.

8. Product Attrition - The attrition values of CMA shall not exceed those of rock salt as measured by ASTM D 4058-81.

9. Specific Gravity - The specific gravity of CMA shall be $\geq$ 1.2 as measured by ASTM D 70-76 using toluene as the displacement liquid.

10. Minimum of 0.4 meg of residual base per gram of sample.

11. Maximum water content of 4%.

Source: after [28] with revisions

Appendix D

Cost of Verglimit Pavement

1. Mass cost of Verglimit

   $1345/tonne, FOB Hamilton, Ontario [52]

2. As % of Asphalt

   Approximate cost of asphalt $40/tonne installed

   Verglimit mixed at ratio of 5% = 50 kg/tonne [52]

   Cost of 50 kg Verglimit 1345 x .45 = 67.25

   Verglimit as % of asphalt cost $\frac{67.25}{40}$ = 168%

3. Above does not include additional mixing costs

Appendix E

Application of Sand and Salt to Ontario Highways

Sanding:

1. Sand is used as an abrasive to provide traction on slippery surfaces. It will be used most often when the temperature is too low for salt to be effective. Sand is most effective in providing traction on dry, hard snow.

2. As a general rule, sand will be used when the temperature is falling below, or not expected to rise above -12°C. However, sand will be used at higher temperatures if traction is required immediately.

3. Sanding, when required, should normally follow after the plowing operations. This minimizes the amount of sand being pushed off to the side of the road.

4. As a general rule, if the pavement is dry and the snow is not packing or sticking, do not sand.

Salting:

1. Salt applied to snow, forms a brine mixture. This reduces the possibility of the snow sticking to, or packing on the pavement. It also prevents ice build-up and allows the plow to remove the snow easier. Salt, assisted by sun, traffic, and warmer daytime temperatures, is also used as a melting agent to eliminate icy conditions.

2. As the temperature gets lower, the effectiveness of the salt decreases until it becomes ineffective.

   Normally, salt should not be applied when the temperature is below -12°C. However, in the presence of sun and heavy traffic volume, which creates a higher road surface temperature, salt can be effective down to a temperature of -18°C.

3. Salting operations, when required at the beginning of a storm, should commence early, before 0.5 cm of snow accumulates, or before sleet or freezing rain produce icy conditions.

   Salting operations should not take place in anticipation of a storm.

4. Salt should be applied a minimum of 0.5 h in advance of plowing to prevent the salt from being pushed off before it has had a chance to work. This is consistent with salt being used to assist in the plowing operations.

   The lower the temperature, the longer it will take for the salt to work.

5. As a general rule, salt should not be applied during night hours to 05:00, since nighttime temperatures are usually lower and sun and traffic volumes are not present to enable salt to work effectively. However, at night, if the temperature is high enough and not dropping, then salting operations may be carried out at the beginning or during the storm, i.e. temperature is above -7°C with wet snow, sleet, or freezing rain occurring. Salting after the storm, to bare the pavement, should be done after 05:00.

6. If the pavement is dry and the snow is not packing, DON'T SALT.

Source: [14]